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A review on combined solar-membrane systems for wastewater treatment in Africa

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Africa's growing water stress and energy access challenges necessitate sustainable wastewater treatment solutions. This review critically examines three emerging approaches: solar-based, membrane-based, and hybrid solar-membrane systems, across the African continent. Solar technologies, including solar water disinfection, photocatalysis, and advanced oxidation processes, demonstrate significant potential in sun-rich regions, achieving more than 90% pathogen and contaminant removal in decentralized settings. Membrane bioreactors (MBRs) and advanced filtration systems show robust performance in industrial applications, with 95%–99% pollutant rejection, though their energy demands remain a significant constraint. Hybrid solar-membrane systems synergize these advantages, as evidenced by case studies in Kenya (solar-MBR for aquaculture, 40% energy autonomy) and Namibia (solar-powered desalination, 99.7% salt rejection). Despite technological promise, adoption barriers persist, including high capital costs, technical capacity gaps, and policy fragmentation. This review analyze 32 implementations across 17 African countries, evaluating performance metrics, scalability, and socioeconomic viability. Key findings highlight the cost-effectiveness and sustainability gains from waste-derived membranes (e.g., geopolymers, recycled plastics, oasis waste), nanoparticle-enhanced photocatalysts (TiO_2/MnO_2), and modular system designs tailored to off-grid and resource-limited settings. The review concludes with policy recommendations to accelerate deployment. These include fostering decentralized systems in peri-urban and rural areas, promoting public-private partnerships to finance infrastructure, and supporting localized research to adapt technologies to diverse hydroclimatic and socio-economic conditions. Together, these approaches offer a viable pathway toward achieving SDG 6 and SDG 7 in Africa.

KEYWORDS

solar-membrane systems, wastewater treatment, circular economy, renewable energy, water reuse, Africa

1 Introduction

Africa faces a dual challenge of water scarcity and energy poverty, with over 300 million people lacking access to clean water and 600 million without reliable electricity (Oluwasanya et al., 2022). In this context, sustainable wastewater treatment technologies leveraging Africa's abundant solar resources (exceeding 2,000 kWh/m^2/year in many regions (Rachid and Najmi, 2024)) and advanced membrane processes have emerged as transformative solutions. Solar-powered systems such as photocatalysis and advanced oxidation processes (AOPs) demonstrate >90% pathogen removal in sun-rich regions like the Sahel (Ganesh Kumar and Kanmani, 2022; Herman-Czezuch et al., 2022), while membrane bioreactors (MBRs) achieve 95%–99% contaminant removal in industrial applications across South Africa and North Africa (De Jager, 2013; Jallouli et al., 2023).

Despite significant advancements, the deployment of sustainable wastewater treatment technologies across Africa remains fragmented due to persistent technical, economic and policy barriers. While standalone solar technologies like solar water disinfection (SODIS) and waste stabilization ponds have achieved success in rural communities (Sansaniwal, 2022), they face inherent scalability limitations. Conversely, membrane systems exhibit robust performance in urban applications, though their substantial energy requirements (3–10 kWh/m^3) limit viability in off-grid regions (Nadeem et al., 2025). Emerging hybrid solar-membrane systems are effectively bridging this gap, as evidenced by Kenya's solar-MBR aquaculture systems achieving 40% energy autonomy (De et al., 2024) and Namibia's PV-powered desalination plants attaining 99.7% salt rejection (Hoffmann and Dall, 2018). This review critically examines three categories of technologies: (1) standalone solar technologies, (2) membrane-based systems, and (3) integrated solar-membrane hybrids through analysis of 32 case studies across 17 African countries. Our assessment compares technical performance benchmarks (including Tanzania's solar-UF/NF system meeting WHO standards at 1.5 kWh/m^3 (Shen et al., 2016)), economic viability, and implementation challenges. Key innovations identified include waste-derived membranes [e.g., brick-based geopolymers (Boushila et al., 2025)], nanoparticle-enhanced photocatalysts (TiO_2/MnO_2), and modular hybrid designs (Mousa et al., 2025). By synthesizing these technological advances with scalable policy frameworks, this work presents a actionable pathway toward achieving SDG 6 (clean water and sanitation) and SDG 7 (affordable and clean energy) across Africa's diverse hydroclimatic conditions.

2 Literature

2.1 Solar wastewater treatment in Africa

Amid the ongoing energy transition and the growing imperative for sustainable access to sanitation, solar technologies are emerging as a key component in wastewater treatment across Africa. A growing body of research underscores the increasing interest in these solutions, particularly in rural and peri-urban areas where access to conventional electricity infrastructure remains limited or absent (Organization, W. H., and Fund, U. N. C., 2021). Despite the continent's substantial solar potential exceeding 2,000 kWh/m^2/year in many regions (Taylor et al., 2022) the adoption and implementation of solar-powered treatment systems remain uneven and fragmented. Table 1 aims to shed light on current trends and to explore opportunities for scaling up the integration of solar energy in wastewater management throughout the African continent.

While solar-based technologies such as SODIS and AOPs offer promising pathogen removal and are well suited for decentralized contexts, they often lack robustness under fluctuating weather conditions (Sansaniwal, 2022). Additionally, despite high treatment performance in lab-scale studies, few long-term or large-scale deployments have been documented in Africa (Elmolla and Chaudhuri, 2010). There is also a lack of comparative life cycle assessments to evaluate environmental impact relative to conventional systems (Pichat, 2016).

2.2 Membrane wastewater treatment in Africa

Membrane processes have proven their effectiveness in treating both domestic and industrial wastewater around the world (Wintgens et al., 2005; Ulanicki et al., 2007; Al Aukidy et al., 2017; Frascari et al., 2018; Nqombolo et al., 2018; Wouter et al., 2019; Issaoui et al., 2022; Othman et al., 2022; Mzahma et al., 2023; Shehata et al., 2023). In Africa, the use of membrane technologies for wastewater treatment has also been documented (Obotey Ezugbe and Rathilal, 2020; Yusuf et al., 2020; Nasir et al., 2022; Phungela et al., 2024). Membrane bioreactors have been used not only for wastewater treatment, but also in combination with post-treatment processes such as microfiltration, ultrafiltration, nanofiltration, reverse osmosis, or electrodialysis, to improve the quality of treated water and thus enable its reuse (Al-Sayed et al., 2018; Tabraiz et al., 2023; Hoinkis et al., 2022). In a context of increasing pressure on water resources, these studies open up promising prospects for more sustainable water management on a continent where water stress affects large portions of the population (Lema, 2025).

South Africa stands out as one of the African countries where the use of membrane processes for wastewater treatment has been adopted by municipalities and industries, with several municipal and industrial wastewater treatment plants using membrane technologies currently in operation (Phungela et al., 2024; Richards et al., 2025). Studies on the application of membrane processes for wastewater treatment have also been reported. For example, Aziz and Kasongo (2021), Aziz and Kasongo (2021) achieved selective reuse levels of municipal wastewater treated by an MBR depending on the type of membrane used for post-treatment (ultrafiltration, nanofiltration, or reverse osmosis). Richards et al. (2025) evaluated the feasibility of reusing effluents from three decentralized membrane bioreactor (MBR) wastewater treatment facilities located in the Western Cape province of

TABLE 1 Overview of solar technologies Used in wastewater treatment in Africa.

Technologies	Definition	Principle	Favorable conditions	Countries of application	References
Solar Water Disinfection (SODIS)	Point-of-use water treatment method that utilizes solar ultraviolet-A (UV-A, 320–400 nm) radiation and thermal energy to inactivate pathogenic microorganisms	Typically, water is poured into transparent PET (polyethylene terephthalate) plastic bottles and exposed to full sunlight for 6–48 h, depending on weather conditions. The combined effects of UV radiation and increased temperature effectively destroy bacteria, viruses, and some protozoa	Well-suited for sunny regions such as the Sahel. It performs best with clear water (turbidity <30 NTU) and under direct sunlight for a minimum of 6 h. SODIS is appropriate for low-income households and emergency situations	Zimbabwe, South Africa and Sahel regions	SODIS (2019) Limaye and Coakley (1998), Conroy et al. (1999), Berney et al. (2006), Sobsey et al. (2008)
Waste stabilization ponds	Natural wastewater treatment technology that uses biological processes in a series of ponds (anaerobic, facultative, and maturation) to treat domestic or municipal sewage	Solar energy promotes the photosynthesis of algae and aquatic plants, which absorb nutrients and contaminants from the water. This natural process helps purify the water while requiring little energy and minimal complex infrastructure	These systems are effective in warm and sunny regions, where evaporation and biological decomposition are optimized, enhancing the performance of anaerobic, facultative, and maturation ponds. The optimal operation of WSPs depends on sustained temperatures above 20 °C and high solar radiation, which promote pathogen die-off and organic matter breakdown	Sub-Saharan Africa (Burkina Faso, Kenya . . .)	(Ronteltap et al., 2014.) Mwamlima et al. (2025)
Solar sludge drying	Natural and cost-effective method for reducing the volume of wastewater sludge by utilizing the heat and radiation from the sun	This process involves spreading the sludge in thin layers on specially designed drying beds or in solar drying units, where it is exposed to direct sunlight for extended periods. The heat from the sun evaporates the water content in the sludge, while the sun's UV radiation can also contribute to pathogen inactivation	Low-income regions with limited energy	Sub-Sahara and east Africa (Senegal, ghana, Benin, Ethiopia, and Malawi) and Egypt	Babayemi and Dauda (2009), Bennamoun (2012), Tun and Juchelková (2018)
Solar photocatalysis	Advanced oxidation process that uses solar light to activate a photocatalyst typically titanium dioxide (TiO_2) to generate reactive species (e.g., hydroxyl radicals) capable of degrading organic pollutants and inactivating pathogens in water	When exposed to sunlight, the photocatalyst absorbs photons and generates electron-hole pairs. These charge carriers interact with water and oxygen at the surface of the catalyst, producing highly reactive species, such as hydroxyl radicals (OH) and superoxide anions (O_2^-)	≥6 h of direct sunlight, ideally >15–20 MJ/m^2/day	South Africa	Mecha et al. (2016), Pichat (2016), Tetteh et al. (2020)
Solar Advanced Oxidation Processes (AOPs)	Group of water treatment technologies that utilize solar radiation to activate chemical oxidants or photocatalysts, leading to the *in situ* production of highly reactive species primarily hydroxyl radicals (OH)	Solar AOPs work by harnessing solar radiation to activate certain chemicals (oxidants) or photocatalysts, which then generate highly reactive oxidative species, mainly hydroxyl radicals (OH)	More than 5–6 kWh/m^2/day of solar energy	The Sahel, East Africa, Southern Africa, South Africa, Morocco, Egypt, Tunisia, and Nigeria	Malato et al. (2002), Elmolla and Chaudhuri (2010), Maifadi et al. (2022), Tony (2023)
Solar distillation	Water purification process that uses solar energy to evaporate water, then condenses the vapor to collect purified water	Water is heated by solar energy, usually in a basin or container designed to capture sunlight. The heat causes the water to evaporate from the surface, the vapor is captured and condensed (often through a condensation system) to collect purified water	Effectively in sunny, arid regions and is particularly useful for producing fresh drinking water from brackish or polluted sources	Morocco, Kenya, Senegal, Algeria	Tiwari et al. (2016), Zlitni (2019), Katekar and Deshmukh (2020), Arunkumar et al. (2022), Laasri et al. (2024)

South Africa. The results showed that effluents from all facilities generally meet national irrigation standards, with only one facility requiring pH correction. The study emphasizes the importance of exploring alternative low-cost technologies for MBR effluent treatment, as well as the need for integrated managed aquifer recharge models to assess different groundwater replenishment scenarios. Meyo et al. (2021), for their part, investigated the use of an MBR as a post-treatment for poultry slaughterhouse wastewater in the city of Cape Town. Following treatment with an Expanded Granular Sludge Bed (EGSB) reactor, the MBR provided additional contaminant reduction, achieving peak removal efficiencies greater than 95% for TSS and COD, and up to 80% for fats, oils, and grease.

In North Africa, several studies on the use of membrane processes for wastewater treatment have been reported in Egypt, Morocco, Tunisia, and Algeria (Al Aukidy et al., 2017; Kitanou et al., 2018; Al-Sayed et al., 2023; Mzahma et al., 2023). In Tunisia, for example, the work of Jallouli et al. (2023) highlighted promising results in the treatment of textile industry wastewater using an immersed membrane bioreactor. A laboratory-scale pilot was used, consisting of a bioreactor (BR) equipped with a filtration unit containing polyester mesh with 30 µm pore diameter, operating at an influent flux of 30 LMH. The results showed a significant reduction in COD and DOC concentrations, reaching average values of 34 ± 10 mg/L and 32 ± 7 mg/L, respectively, corresponding to removal efficiencies of 96.0% ± 1.1% and 94% ± 1.05%. Removal rates of 96% for COD and 85% for color were also achieved. Ammonia (NH_3) was removed at a rate exceeding 97%, sulfates at 41%, and phosphates at 37%. The final pollutant concentrations were well below regulatory limits, demonstrating the effectiveness and viability of this technology for treating textile wastewater. In addition, Recent studies highlight the potential of waste-derived membranes for sustainable oily wastewater treatment. Research demonstrates that geopolymer membranes fabricated from waste bricks achieve >90% oil rejection when cured at 60 °C–80 °C, with an optimal liquid-to-solid (L/S) ratio of 0.30–0.35 enhancing cross-linking density and mechanical strength (Boushila et al., 2025). Similarly, work shows that membranes produced via phase inversion using discarded plastics and oasis fibers exhibit >90% separation efficiency, with polymer composition and pore structure governing permeability and fouling resistance (Zrelli et al., 2023). Additionally, ceramic membranes derived from oasis waste remove >85% of oils and suspended solids from car wash wastewater, outperforming conventional polymeric membranes in chemical stability and fouling resistance (Zrelli et al., 2022). Collectively, these studies underscore the viability of repurposing industrial and agricultural waste into high-performance membranes, offering cost-effective, eco-friendly alternatives for wastewater remediation while addressing waste valorization challenges. In Egypt, Abdel-Shafy and Abdel-Shafy (2017) also reported studies on the combined use of MF, UF, and NF for the extraction of valuable compounds from urine, as well as the use of MBRs for the treatment of blackwater and municipal wastewater. The organic loads in the MBR effluent consistently met the required standards. The results demonstrated high efficiency of the membrane bioreactor (MBR) for wastewater treatment. Applications of membrane technologies have also been reported in Burkina Faso, West Africa Sawadogo et al. (2018a), Nouhou Moussa et al. (2023), Nouhou Moussa et al. (2023) used a membrane bioreactor (MBR) for the treatment of brewery and sugar industry wastewater. These studies demonstrated chemical oxygen demand (COD) removal rates of up to 95%. The use of nanofiltration and reverse osmosis following the MBR led to organic matter and mineral removal rates reaching 99%, resulting in effluents suitable for reuse. Taking advantage of the favorable climatic conditions of the Sudano-Sahelian zone, anaerobic operation led to biogas production volumes of 0.21 L biogas/g COD removed for brewery wastewater (Sawadogo et al., 2018a; Sawadogo et al., 2018b; Sawadogo et al., 2022) and 0.32 L CH_4/g COD removed for sugar industry wastewater (Nouhou Moussa et al., 2023; Sawadogo et al., 2024). The high temperatures typical of the Sahelian climate are therefore favorable for anaerobic operation of the membrane bioreactor.

In East Africa Gukelberger et al. (2020), studied the use of a membrane bioreactor (MBR) for the treatment of domestic wastewater as part of a sustainable water management approach in the Lake Victoria region. The MBR was used to treat domestic wastewater to provide make-up water for a recirculating aquaculture system (RAS). They reported that the application of MBRs in wastewater treatment holds promising potential, not only for recirculating aquaculture systems, but also for the treatment of wastewater from fish processing in the Lake Victoria region.

While the performance of these waste-derived membranes is promising with oil rejection rates above 90% and strong chemical stability scalability remains a challenge. Most results stem from laboratory or pilot-scale studies. Furthermore, membrane fouling, mechanical durability, and variable composition of source waste materials could affect long-term reliability (Noureddine, 2021; Zrelli et al., 2023). There is a need for further field validation in diverse African conditions to assess lifecycle costs and maintenance requirements.

Membrane systems deliver excellent contaminant removal, especially in industrial settings; however, high energy requirements, membrane fouling, and costs of maintenance limit their accessibility in off-grid or rural areas. Moreover, although waste-derived membranes are an exciting innovation, their long-term durability and performance in real-world settings remain insufficiently explored (Obotey Ezugbe and Rathilal, 2020; Nasir et al., 2022).

2.3 Combined solar-membrane systems in Africa

Combined solar-membrane systems function as sustainable water treatment solutions in African areas because they address both the water scarcity problem and energy access issue. Membrane systems utilizing solar power combine RO with

MBR and the joint UF-NF system to supply water throughout various parts of Africa.

The countries of Kenya Uganda and Tanzania together lead the way for decentralized solar-powered water treatment in East African regions. The Membrane Bioreactor (MBR) serving Kisumu Kenya's tilapia farming receives daily 3–4 cubic meters of wastewater using a 14.3 kWp solar-powered system. A novel combination design obtains 40% self-power along with exceptional ammonium extraction capacities that guard fish health from toxicity and support thriving aquatic farming operations. The design's ability to scale up leads to both environmentally sustainable fish farming alongside employment generation in the region thereby strengthening the area's economic and environmental resistance (De et al., 2023). In Kampala Uganda they operate an MBR-GAC system powered by 7 kWp solar energy which processes 7–8 cubic meters of wastewater daily for irrigation needs coupled with toilet flushing. An aquaculture wastewater treatment system combined filtration tanks with denitrification and nitrification tanks, yet it retrieved most materials from local suppliers except for the monitoring unit and membrane module. The PES membrane module operating at 125 mbar pressure had a 25 m^2 flat surface area that delivered permeate flux between 10 and 15 $L/m^2/h$ while being measured periodically. The plant accomplished COD and TOC decreases of 50% while the nitrification reached an 80% level. The measured average rate of denitrification equaled 20%. Water quality significantly improved when the modified GAC installation managed to eliminate 90% of pharmaceutical residues. The acclimation of sludge in the system led to a remarkable 75% improvement in diclofenac removal efficiency because of increased hydraulic retention time and sludge retention time. The integration of supercapacitors with the system provides backup power for continued operation during blackouts and delivers 43% autonomous clean energy capabilities thus offering a sustainable and durable solution for hospital wastewater treatment (De et al., 2024).

A team evaluated solar-powered membrane filtration for treating contaminated water in Tanzanian rural areas having limited access to electricity along with clean water. The system applies an ultrafiltration step followed by nanofiltration to reach World Health Organization drinking water requirements (fluoride <1.5 mg/L) when treating water with 50–60 mg/L fluoride and 255 mg/L TOC organic matter in the natural water sources.

Solar photovoltaic panels directly wired to the system make the system independent from both power grid connections and power storage systems while solar irradiance varies. The clean water production rate reached 1,200 L per day while the energy consumption rate amounted to 1.5 kWh for every cubic meter of water. The system faced both organic matter buildup in the membrane and user acceptance towards the final product since it was deemed contamination-free (Shen et al., 2016; Schäfer et al., 2018).

North Africa leverages solar-membrane systems for industrial and municipal wastewater treatment. Researchers in Tunisia operated two membrane bioreactors at pilot scale next to a typical activated sludge treatment system in order to analyze water quality standards and energy consumption. The evaluation of MBR system energy usage indicated results matching or outperforming conventional system efficiency levels which stood at 3 kWh/m^3. A solar integration system maintains diesel generator independence and demonstrates equivalent specific energy requirements to conventional systems to generate high-quality treated water. Integrated solar-MBR technology presents a sustainable method for decentralized domestic water treatment throughout North African regions as it provides effective irrigation solutions (Skouteris et al., 2014). In addition, the integration of green-synthesized TiO_2/MnO_2 nanoparticles into solar-powered membrane systems for the treatment of pulp and paper industry wastewater, with a particular focus on applications in Africa, especially Egypt. The solar-membrane system delivered outstanding performance since it eliminated chemicals present in wastewater by 85%–90% of COD and color together with suspended solids (Abed et al., 2024; Mousa et al., 2025). The introduction of TiO_2/MnO_2 nanoparticles into the system enhanced both photocatalytic under solar conditions and membrane flux and reduced fouling which increased membrane longevity. Operation of solar systems dramatically decreased running expenses making it an eco-friendly affordable method appropriate for Egypt's water-scarce industrial regions.

Solar desalination combined with modular treatment has become a large-scale technology leader across Southern Africa. South African specialists have implemented solar energy into modular drinking water systems while integrating Combined Solar-Membrane Systems to solve water scarcity problems. The implemented systems demonstrated exceptional performance by reducing pathogens by 95% and attaining turbidity levels lower than 1 NTU while maintaining substantial total dissolved solids (TDS) elimination. The modular units leveraged solar energy while exploiting abundant sunlight for

TABLE 2 Comparative summary of technologies (Richards and Lipnizki, 2023; Zrelli et al., 2023; De et al., 2024; Boushila et al., 2025).

Technology type	Cost-effectiveness	Environmental sustainability	Deployment potential (Africa)
SODIS and Waste Stabilization Ponds	Very low capital and operational cost; limited maintenance	High passive solar energy, minimal chemicals	Ideal for rural and low-resource settings (e.g., Sahel, Sub-Saharan Africa)
Advanced Solar AOPs and Photocatalysis	Moderate cost; depends on catalyst reuse	High solar driven, but requires chemical inputs	Suitable for peri-urban regions; requires technical training
Membrane Bioreactors (MBRs)	High initial cost; moderate O&M	Medium energy intensive, but enables reuse	Effective in urban/industrial settings (e.g., South Africa, Tunisia)
Waste-derived Membranes	Low to medium cost (if locally sourced)	High supports circular economy, low carbon footprint	Promising for decentralized use if scaled locally
Solar-Membrane Hybrids	High upfront cost; cost-saving over time via energy autonomy	Very high renewable energy + advanced treatment	Suitable for off-grid and peri-urban areas (e.g., Kenya, Namibia); replicable at pilot-to-medium scale

delivering sustainable and decentralized water solutions with energy efficiency. The results confirm that Combined Solar-Membrane Systems exhibit great potential for improving water access in distant South African areas which lack proper water services (Kumar et al., 2022). The Witsand facility in South Africa demonstrates an outstanding model of battery-independent solar desalination systems. The plant relies on Osmosun® specialized technology to support reverse osmosis performance by automatically integrating grid power when solar input decreases especially during nighttime (Richards and Lipnizki, 2023).

Namibia opened its initial solar-powered desalination plant at the University of Namibia's Henties Bay campus after partnering with Finnish companies. Solar PV reverse-osmosis technology operates at the Henties Bay plant to generate 3,500 L/h of clean water with an energy requirement of 2.five to three kWh/m^3 that outmatches diesel-based systems by 40%. This desalination system effectively gets rid of 99.7% salts as well as 99.9% bacteria and 99.5% viruses while meeting WHO requirements and lowering the TDS from 35,000 ppm to less than 500 ppm. This plant reduces annual CO_2 emissions by 12 tons in addition to minimizing operational expenses through fossil fuel system reduction of 50–60 percent. This system combines modular convenience through which users can begin operations at 5 m^3 per day for villages but can expand to 1,000 m^3 per day for cities and features hybrid power backup that maintains system reliability beyond 95% standards. Treated water obtained through the filtration process helps increase crop production in experimental farms by 20%–30% as demonstrated through pilot projects. This model demonstrates solar desalination's viability for arid regions, combining zero-emission operation, cost savings, and scalable water security—a blueprint for sustainable development in water-scarce areas (Hoffmann and Dall, 2018; Antti, 2019) (Table 3).

TABLE 3 Summary of solar and membrane wastewater treatment technologies across 17 African countries.

Country	Technology type	Application/project	Key outcomes	Challenges	References
Kenya	Solar-MBR	Tilapia aquaculture, Kisumu	40% energy autonomy, improved water reuse	Initial investment, maintenance needs	De et al. (2024)
Uganda	MBR-GAC + PV	Hospital wastewater, Kampala	90% pharmaceutical removal, 43% solar autonomy	Imported modules, technical complexity	De et al. (2024)
Namibia	Solar desalination (PV-RO)	Henties Bay Campus	99.7% salt rejection, 3500 L/h output	Cost of hybrid backup, scaling logistics	Hoffmann and Dall (2018)
Tanzania	Solar UF/NF	Fluoride removal from boreholes	Met WHO drinking standards (1.5 kWh/m^3)	Membrane fouling, user acceptance	Schäfer et al. (2018)
South Africa	MBR and solar modular systems	Municipal and car wash wastewater treatment	>95% pathogen removal, <1 NTU turbidity	Intermittent power, O&M capacity	Richards et al. (2025)
Tunisia	MBR + solar + TiO_2 Geopolymer membrane	Textile and paper industry Oily wastewater	85%–90% COD and color removal, lower fouling >90% oil rejection, good mechanical resistance	Scalability, nanoparticle recovery Pilot scale, curing variability	Mousa et al. (2025) Boushila et al. (2025)
Egypt	MF/UF/NF + MBR	Blackwater and urine valorization	High organic load removal, nutrient recovery	Cost, sludge disposal	Abdel-Shafy and Abdel-Shafy (2017)
Burkina Faso	Anaerobic MBR + NF/RO	Brewery and sugar factory wastewater	99% COD removal, 0.32 L CH_4/g COD	Membrane cleaning, effluent reuse perception	Sawadogo (2018)
Morocco	Solar distillation	Rural drinking water	High-quality distilled water, simple operation	Low throughput, weather dependency	Laasri et al. (2024)
Algeria	MBR textile wastewater	Textile effluent pilot (Alger)	96% COD and 85% color removal	Fouling, effluent discharge norms	Jallouli et al. (2023)
Nigeria	Solar AOPs	Urban sludge treatment	Effective disinfection, decentralized application	Oxidant management	Tony (2023)
Senegal	Solar sludge drying	Municipal sludge	Cost-effective drying, pathogen inactivation	Weather-dependent	Bennamoun (2012)
Ghana	Solar drying	Sludge stabilization	Reduced volume, basic infrastructure	Requires land, exposure to elements	Babayemi and Dauda (2009)
Ethiopia	Waste stabilization ponds	Municipal wastewater	Pathogen reduction, low O&M	Space requirement, odor control	Mwamlima et al. (2025)
Malawi	Solar pond systems	Community wastewater	Passive treatment, low cost	Long retention time, performance monitoring	Ronteltap et al. (2014)
Benin	Solar sludge drying	Sludge treatment	Drying performance acceptable	Dust control, process time	Tun and Juchelková (2018)
Zimbabwe	SODIS	Household water treatment	Effective microbial reduction in PET bottles	Turbidity limits, behavior adoption	SODIS (2019)

A successful implementation of large-scale solar-membrane wastewater treatment systems in Africa needs an organized multistakeholder collaboration. Key actions should include: creating enabling policy environments with targeted financial incentives to accelerate technology adoption; prioritizing context-specific research to adapt systems to local hydrological and climatic conditions; strengthening cross-sector collaboration through public-private partnerships to mobilize technical and financial resources; mainstreaming these solutions into national water security and climate resilience frameworks; and building local capacity through vocational training and community engagement programs to ensure sustainable operation and maintenance. A comprehensive approach tackles both technological implementation alongside sustainable operation to consolidate the technology's potential benefits for enhancing water security throughout various African regions.

Despite their innovative design, some modular hybrid systems face limitations. For example, while energy autonomy is improved through PV integration and supercapacitors, performance can be inconsistent under fluctuating solar irradiance. Additionally, reliance on imported membrane modules or electronic monitoring systems may increase costs and reduce local ownership (Schäfer et al., 2018; Richards and Lipnizki, 2023). These factors should be carefully considered when scaling up in remote or resource-constrained areas.

A comparative Assessment of Technologies Based on Cost-Effectiveness, Environmental Sustainability, and Deployment Feasibility in Diverse African Contexts is given in table 2.

To facilitate cross-country analysis, the Table 3 summarizes the distribution, effectiveness, and contextual challenges of each technology.

Hybrid systems represent a promising integration of solar energy and membrane performance, especially for remote or semi-urban areas. However, their technical complexity, dependence on imported components (De et al., 2024), and lack of skilled local operators (Richards and Lipnizki, 2023) present real deployment barriers. There is also a gap in standardized methodologies for evaluating cost-benefit and resilience under climate variability (Zrelli et al., 2023). Research should focus on optimizing designs for modularity and local manufacturing potential.

3 Conclusion

The integration of solar and membrane technologies presents a promising and scalable pathway for advancing sustainable wastewater treatment across Africa. Leveraging the continent's abundant solar resources and the growing accessibility of membrane systems offers a unique opportunity to address both water scarcity and energy poverty. From basic solar disinfection methods such as SODIS to advanced oxidation and membrane-based processes, these technologies have demonstrated strong potential in decentralized, off-grid, and resource-limited settings. Among them, combined solar-membrane systems stand out for their ability to reduce operational costs, improve treatment efficiency, and achieve energy autonomy. Successful case studies from solar-powered membrane bioreactors in Uganda and Kenya to solar desalination systems in Namibia and South Africa demonstrate the feasibility of modular, decentralized solutions. Notably, innovations such as waste-derived membranes, green-synthesized photocatalysts (e.g., TiO_2/MnO_2), and scalable modular units improve cost-effectiveness and local adaptability. These approaches not only reduce dependency on conventional infrastructure but also support circular economy goals by valorizing industrial and agricultural residues.

Nevertheless, the adoption of these advanced technologies must be contextualized. Critical issues such as membrane fouling, uneven solar energy yields, limited local manufacturing capacity, and social acceptance of treated effluents remain underexplored. Addressing these constraints through targeted R&D, vocational training, and adaptive deployment strategies will be key to successful and sustained implementation.

To accelerate scale-up, the following policy and institutional actions are recommended.

- ✓ Develop enabling regulatory frameworks that recognize and support decentralized hybrid systems.
- ✓ Promote public-private partnerships to reduce capital barriers, as seen in the Namibian and Kenyan case studies.
- ✓ Invest in local innovation ecosystems for membrane manufacturing and solar integration.
- ✓ Embed these technologies into national water security and climate resilience agendas, ensuring alignment with SDG 6 and SDG 7.
- ✓ Prioritize inclusive capacity building through technical training and community sensitization to improve ownership and maintenance sustainability.

In sum, the deployment of combined solar-membrane systems, when guided by robust policies and context-aware strategies, holds transformative potential for advancing equitable, low-carbon, and resilient water services across the African continent.

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